Title: Apparatus for centrifuge modelling of twin-tunnel construction

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Abstract: In urban areas it is common for pairs of tunnels to be used as a method for building rapid transit systems. Driven by an increasing population and demand for services, tunnels are more widespread in their use than at any previous time. Construction of any form of tunnel causes ground movements which have the potential to damage existing surface and sub-surface structures. Modern tunnelling practice aims to reduce these movements to a minimum but there is still a requirement for accurate assessments of possible damage to structures resulting from settlements. For tunnels driven in clay, superposition of settlement predictions made by considering a single tunnel is an accepted method used to estimate movements around pairs of tunnels. Previous research, particularly numerical studies, has indicated that this may not necessarily be sufficient. In this paper a series of centrifuge model tests designed to investigate settlements related to twin-tunnel construction are described. The development of the experimental apparatus for sequential twin-tunnel construction with variable centre-to-centre spacing and volume loss is described in detail.

Key words: tunnels and tunnelling, geotechnical engineering, models (physical)

Notation:

C	Tunnel cover
D	Tunnel diameter
g	Acceleration due to gravity
i	Horizontal distance from the tunnel centre-line to the point of inflexion of the settlement trough
S_{max}	Maximum surface settlement

Introduction

Tunnelling is a widely used method for creating transport links, communication systems and for housing other services (water, cables etc). In urban regions, where available surface space is limited, tunnelling is used extensively. Due to the relative ease with which tunnels are constructed through clayey soils this method has grown in popularity. A Tunnel Boring Machine (TBM) is one of the most efficient construction methods for tunnelling through this medium, largely because of technological advancements making this a highly automated system with a high level of precise control. Irrespective of the method used, tunnel construction causes ground movements which have the potential to cause damage to existing structures. Modern tunnelling practice aims to reduce these movements to a minimum but there is still a requirement for accurate assessments.

Due to the nature of the cutting process the bored shape of a tunnel will always be larger than the final shape. The difference in these two volumes has been described by the term 'ground lost' or, the more frequently used, 'volume loss' and is usually expressed as a percentage of the excavated face area. This phenomenon manifests at the surface as a transverse settlement trough. Field observations and research have shown this to propagate throughout the soil mass causing possible damage to existing structures (Mair & Taylor, 1997). One accepted estimation of the settlement is a Gaussian curve in the plane perpendicular to the advancing tunnel face (Peck, 1969). Construction guidelines have been developed based, largely, on research from single tunnel arrangements (e.g. Peck (1969), Mair (1979), Taylor (1984) and Attwell & Yeates (1984)). For a full discussion on potential sources of ground deformation during tunnelling see Mair & Taylor (1997).

Mass transit tunnelling systems are often constructed in pairs (e.g. Jubilee Line Extension described by Burland *et al.*, 2001). Superposition of single tunnel predictions is an often utilised method to estimate movements around pairs of tunnels but implicit in this method is the assumption that construction of the second tunnel is unaffected by the presence of the first tunnel. Previous numerical studies have indicated that superposition may not necessarily be sufficient and this is reflected to some extent in the field observations. Hunt (2005) explored the influence of constructing tunnels in close proximity using the finite element method and proposed some deviation from the superposition technique. In a number of major projects there has been extensive monitoring of ground movements and tunnel behaviour throughout the projects life cycle. Examples of these projects are St James Park in UK (Nyren, 1998), Lafayette Park in USA (Cording & Hansmire, 1975), and The Heathrow Express in UK, (Cooper & Chapman, 1998). In all these case studies observations of surface settlement data indicated asymmetry of the movements generated by each tunnel.

The main aim of the current research programme is to explore the behaviour of the ground when constructing tunnels with a close spacing in over-consolidated clay. The project is primarily based around centrifuge model tests. In order to perform this task a sophisticated apparatus was developed which is described herein.

Previous centrifuge modelling of tunnels in clay

Modelling tunnelling procedures in clay using a geotechnical centrifuge can pose significant difficulties relating to accurate simulation of the construction process. The main difficulty is the simulation of, or actual removal of soil from the model to form the tunnel cavity. Methods have been developed by a number of research groups with varying degrees of complexity and success.

Mair (1979) simulated an excavation of a circular tunnel cavity in a centrifuge by using a pressurised air-filled rubber bag. This involved increasing the air pressure to equal the soil overburden in order to support the tunnel cavity during spin up and pore pressure equalisation and then decreasing this pressure to simulate a failure. Measurements of ground deformation arising from particular volume losses were then made by inspection of the appropriate portion of the results set. Wu *et al*. (1998) and Lee *et al*. (2006) applied the pressurised bag method to twin-tunnel arrangements. The tests simultaneously reduced the pressure until collapse was observed and it may be argued that this is not a realistic interpretation of the construction process, as there was no delay between each tunnels construction.

Imamura *et al*. (1998) utilised an in-flight excavator to construct the tunnel cavity, the spoil from which was retained within the strongbox in order to negate any out-of-balance loading. The package size available at City University London would have made this type of system impractical to model. Additionally, the tests produced volume losses that may be considered unrealistically high particularly when compared with field measurements in stiff clays.

Jacobsz (2002) developed apparatus to enable modelling of small strain movements around a single tunnel in sand close to another structure. Construction in flight was simulated by draining water that was supporting the tunnel cavity during pore pressure equalisation. This allowed accurate control of the volume loss. It was this approach that the current twin-tunnel volume loss apparatus developed at City University London was based upon.

This paper details the developments in centrifuge apparatus to facilitate the simulation of sequential twin-tunnel construction. An initial test series established results from single tunnel apparatus using either air or water for cavity support which gave comparative values of surface settlement for a given volume loss (Divall, 2010). Subsequently, the apparatus was developed in order to perform a second test series. These tests simulated twin-tunnel side-by-side arrangements i.e. parallel tunnels constructed at equal depth from ground surface to axis level. Both these apparatus are described in detail and typical test results presented.

Experimental design

Introduction

Two sets of apparatus (single tunnel and twin-tunnel) were developed however, a significant number of features were common to both experimental series. Experiments were performed in a plane strain strong box at 100 g. Models consisted of a preformed circular cavity (or cavities) in over-consolidated clay. The aim of the apparatus was to provide tunnel support using a fluid and to allow that fluid to be removed in order to simulate volume losses. The overall layout for the models is detailed in Figures 1 and 2.

Model geometry

The internal dimensions of the strong box available for the soil model are shown in Figure 1. The base plate of the strong box has grooves cut to give a path for drainage during the consolidation process. Ports are present in the back-wall for installation of pore pressure transducers and the fluid feed for the tunnels. During the model making stage the front-wall of the strong box can be removed. This can then be replaced with poly (methyl methacrylic) (PMMA) windows enabling observation of the subsurface ground movements during the test.

The prepared clay sample was trimmed to a cover to diameter ratio (C/D) equal to 2. The tunnel axis level was approximately 80 mm above the base of the strongbox. A single tunnel was bored in the centre of the model or twin-tunnels were bored equally spaced from the model centre-line dependent on the particular test.

Soil used and stress history

The clay used was Speswhite kaolin supplied by Imerys, England. Usual practice for model making is to prepare slurry to a water content of 120 %. Samples are consolidated, in a hydraulic press, under a vertical stress of 500 kPa followed by swelling to 250 kPa before model preparation and further in-flight consolidation.

The centrifuge

City University London's centrifuge facility comprises of an Acutronic 661 geotechnical centrifuge with a radius of 1.8 m. This system has the capacity to test models weighing up to 200 kg at 200 g. Details of the facility are given by Grant (1998), including a description of the digital image processing capability used for subsurface measurements.

Apparatus for single tunnel model (Apparatus A)

Apparatus A comprised three elements:

- Tunnel system
- Support window
- Fluid control system.

Tunnel system

The tunnelling system was based on a similar arrangement first described by Jacobsz (2002) and is shown in Figure 3. The tunnel cavity contains a fluid filled apparatus that supports the clay during in-flight consolidation and allows that fluid to be removed during construction simulation. The system comprised two aluminium circular end pieces connected by a hollow rod acting as a mandrel. These pieces were set at either ends of the tunnel cavity. The end pieces were of 47 mm diameter and 6.5 mm thickness. The diameter was chosen because the system needed to be placed within a preformed 50 mm diameter cavity. The thickness is of a size sufficient to provide for an O-ring groove around the circumference.

The end pieces secured a natural latex membrane in position (Figure 3, detail). The membrane was 0.5 mm in thickness and 240 mm long. During the model making stage the bag was trimmed as appropriate after fitting.

The tunnelling system was sealed by placing 44.5 mm O.D. O-rings over the membrane at the recesses. The O-rings sat proud of the outer diameter and were clamped in place by tight fitting brass circular clasps. The clasps had an outer diameter of 49.9 mm and internal diameters made to fit.

The latex membrane was filled with water (a virtually incompressible fluid) which supports the preformed cavity during pore pressure equalisation. The tunnelling system was designed to facilitate a wide range of volume losses which is achieved by extracting a set volume of water from inside the rubber bag through the hollow rod. This rod had a 6 mm outer diameter and a 3 mm internal diameter. Three 2.5 mm diameter holes were drilled radially to allow for drainage.

One of the end pieces was screwed onto the rod and sealed as previously outlined. The opposite end piece was secured to an externally threaded brass fitting. The fitting allowed a fluid supply through the strongbox back-wall and supported the tunnelling system at one end during the testing stage. The pipe joined to the fluid controlling system. Once assembled, the tunnel support system is filled with water prior to installation within the clay. A bleed screw, sealed with an O-ring, allows the tunnel to be de-airing during the model making stage, ensuring a stiff tunnel cavity support.

The overall length of the apparatus was 210 mm as compared with the internal width of the strongbox which was 200 mm. This required the end of the apparatus to sit within a recess cut into the front window of the strongbox. This feature was considered important as it ensured the soil was solely supported by the fluid filled membrane and any observed soil movements would not be influenced by the stiff metal components.

Support window system

To observe the subsurface ground movement in a plane strain centrifuge model, it is usual practice to replace one wall of the strong box with a clear PMMA window. Cameras are used to record images at set intervals during the experiment and a digital image analysis system used to obtain subsurface movements (Taylor *et al.*, 1998). This process utilises a grid of reference targets etched onto the clay-facing side of the observation window.

The existing window was 83 mm thick. Modifying this window to accommodate the various configurations of tunnels was considered uneconomical and therefore a second, inner PMMA window was used. This inner PMMA window was referred to as the support window.

The support window is made from 12.7 mm thick PMMA sheet. It was positioned between the 83mm thick observation window and the strong box, clamped in position by bolts that pass through both windows. The support window had a 10 mm deep circular recess for the end piece of the tunnelling system. As this was a blind recess, seepage of pore water from the model was prevented. The aim of the recess was to remove stiff elements of the tunnel support system from within the soil mass as well as restricting deflection of the apparatus under high g.

The control targets for the image analysis were machined onto the support window using a computer numerical control (CNC) mill and their positions were therefore known to a high degree of accuracy.

Fluid control system

The fluid control system was based on similar apparatus described by Jacobsz (2002). The system can be divided into two parts (Figures 2 and 4) for different stages of the testing process. These parts were

- The tunnel support pressure standpipe
- The fluid removal equipment.

The pressure within the preformed tunnel cavity was controlled by a standpipe situated on the swing-bed. The over-flow was set at a level to provide a pressure at the tunnel axis level equal to the soil overburden. During spin-up the water and the soil are subjected to the same gravitational increase. This meant the pressure inside the cavity did not need to be controlled manually in the same way as some pressurised air systems (e.g. Mair, 1979).

The fluid extraction system (Figure 4) comprised a bishop ram driven by a 48 V servo motor. Control of the flow of fluid to the tunnels is achieved using quarter-turn plug valves controlled by 24 V rotary solenoids. The bishop ram acted as a syringe and provided storage for fluid withdrawn from the tunnelling system. The bishop ram was controlled remotely by the servo motor which drives a cog secured to the lead screw of the bishop ram via a toothed bar. Use of the toothed bar accommodates the lead screw of the bishop ram moving upwards as fluid is withdrawn.

The fluid controlling system was connected to the tunnelling system and the standpipe by 3 mm pipe. Stainless steel pipe was chosen because plastic or rubber tubing may have collapsed or kinked at high g, impeding the flow of fluid within the apparatus.

The completed system was calibrated prior to testing to ascertain the volume of fluid moved in a single revolution of the servo motor. 1 revolution was equal to 1.08 ml; hence, for a 3 % volume loss approximately 9 revolutions would be required.

Apparatus for twin-tunnel model (Apparatus B)

Introduction

The development of the twin-tunnel models involved a number of modifications to the above described apparatus. The overall concept for the system was identical (i.e. fluid support that could be removed to simulate volume loss) and each part performed similar functions to those previously discussed. Modifications were applied to three key elements.

Twin-tunnel system

As well as the obvious need to have two tunnel supporting components a number of other modifications were made to the previously described design. Principally, the outer diameter of the tunnels was changed to 40 mm. This change was to ensure the observed movements were not affected by boundary conditions due to the restricted size of the strong box. Using semi-empirical methods such as those described previously, a settlement trough was predicted for each individual tunnel. Accepting this simplification, even at the maximum proposed centre-to-centre spacing the extent of the settlement troughs were not predicted to reach the side walls of the strong box.

The two end pieces for each tunnel are of a similar design to that described above but with an outside diameter of 37 mm. Once again the latex membrane was secured at either end with an O-ring and brass clasp. Additionally, the centre support rod was extended by another 10 mm to give an overall length equal to 220 mm. Combined with a recess machined into the rear face of the strong box this modification avoided the soil being in contact with any of the metal parts of the system. This was designed to completely remove any influence of the stiff parts on the soil movements.

Twin-Tunnel support window system

A twin-tunnel support PMMA window was fabricated. The new window had external dimensions equal to the first (Figure 5). This was fixed to the strong box with the same pattern of bolt holes as described in Apparatus A.

Twin-tunnel back-wall/plug system

A modified strong box back-wall was designed to support the tunnel apparatus. The strong box's rear wall was fabricated from 24.5 mm thick aluminium plate. The new back-wall was designed as a direct replacement for the existing wall and contained an insert to allow for variations in the centre-to-centre tunnel spacing. A series of bolts secured this insert within the modified strong box back-wall and sealed against an O-ring. This arrangement was beneficial as it allows different inserts to be manufactured rather than having to machine a series of replacement walls for the strong box. The insert is of a size that can potentially allow variation in tunnel centre-to-centre spacing between zero and six tunnel diameters.

Model preparation

After the sample was removed from the consolidation press it is imperative that it is not allowed to dry out. Usual practice was to seal the exposed surfaces of the clay before and during model making as quickly as possible with silicone oil.

The front-wall of the strong box was removed to gain access to the clay front surface. A specially fabricated jig was clamped to the front of the strong box and a square aluminium cutter used to trim excess clay from the surface. To bore the tunnels a second jig was fitted to the front of the strong box (Figure 6). A cutter guide could then slide along the frame to the required horizontal position allowing accurate boring of the tunnel cavities. The tunnel cutter was a 40 mm outer diameter circular seamless tube. Once the tunnels were cut a separate guide was clamped to the front of the strong box so that image analysis target beads could be pressed into the front surface of the clay.

At this stage the preparation of the clay was complete. The apparatus was placed inside the tunnel cavity/cavities. It must be noted that every precaution was taken to bleed air out. Screwed to the back of the tunnel apparatus were fittings allowing for fluid in-feed. These fittings also contained pressure transducers to monitor the tunnel pressures at the centre-line.

Prior to being bolted in place, the support window was lubricated with a high viscosity, clear silicone oil to reduce interface friction. The support and observation windows were placed carefully onto the front of the strong box. The fluid controlling apparatus could be placed onto the side and bolted securely through the windows. The piping was connected and deaired. Finally, using a syringe, the tunnel membranes were inflated to completely fill the cavity/cavities.

A rack containing Linear Variable Differential Transformers (LVDTs) was bolted to the top of the strong box to measure vertical surface settlement. The arrangement of the LVDTs was such that symmetry of settlements about the centre-line could be verified. The distribution of pore water pressures in the model during the consolidation and testing stages were monitored by Druck pore pressure transducers. These were embedded into the clay during sample preparation.

Testing for simulated single tunnel excavations (Apparatus A)

The final steps were to weigh the model and place it on the swing. 450 ml of silicone oil was poured onto the top surface to prevent evaporation of pore water from the clay during the test. Once the power supplies, solenoid valves and transducers were connected the final checks were made and the test started.

The test procedure was as follows:

- To support the cavity during spin-up the whole system was open to the tunnel standpipe and, therefore, did not need to be regulated
- When the model reached 100 g the pressurised tunnel was isolated from the standpipe using the plug valve and left, at least over night, for the pore water pressures to reach equilibrium
- To simulate tunnel construction fluid was drained from the tunnel apparatus using the fluid control equipment.

Testing for simulated sequential tunnel excavations (Apparatus B)

After pore water pressure equilibrium had been reached in the model the test procedure was as follows:

- The valve to Tunnel B was closed allowing Tunnel A to be solely controlled by the fluid controlling system
- Water was drained from Tunnel A to simulate tunnel construction
- A time period representing a construction delay was observed
- During this period the valve to Tunnel A was closed and Tunnel B opened
- Once the construction delay time had elapsed fluid was drained from Tunnel B.

The centrifuge was usually run for at least an hour post-test to allow for any longer term movements to develop.

Typical data – Apparatus A

The single tunnel tests were performed to prove that the apparatus could reproduce patterns of ground movement that were commensurate with previous work (experimental, numerical or field measurements). Whilst a large quantity of data is obtained from each test (e.g. surface and sub-surface settlements and pore pressure changes) only the surface settlements are discussed here. This allows comparison with previous work, particularly where Gaussian distributions have been shown to be a good fit to the settlement data.

It should be noted that there were a number of problems associated with the initial tests such as leaks from the latex membranes where they failed to seal at the ends and failure of the plug valves to completely close. These problems were solved by using a thicker O-rings and changing the orientation of the rotary solenoid such that the high gravitational field did not interfere with the operation.

Observed surface settlements

Figure 7 shows the surface settlement for a single tunnel experiment where the volume of fluid extracted from the tunnel is 3.2 % of the total. The data has been normalised with respect to the tunnel diameter. A simple Simpson rule integration of these data shows the volume loss apparent at the surface to be 3 %. Additionally, a Gaussian curve was fit to the data in the manner described by Grant (1998) and it is worth noting the exceptionally high level of agreement between this and the measured data. The volume loss determined from the curve fitting exercise is also 3 %, agreeing very closely with the actual volume of water extracted from the tunnel. Table 1 shows comparisons of this experimental data to various published predictive methods. S_{max} and i are parameters controlling the magnitude and shape of the Gaussian distribution. It may be noted that good agreement is seen between the experimental results and Mair *et al*. (1981) whilst the predictions of Clough & Schmidt (1981) and Verrujit & Booker (1996) compare less favourably due to differences in the method of obtaining the parameter i.

Typical data – Apparatus B

Observed surface settlements

Figure 8 shows results from a twin tunnel test where the centre to centre spacing of the tunnels is 3 tunnel diameters. Again, the data is normalised with respect to the tunnel diameter. With reference to the figure, Tunnel A is excavated prior to Tunnel B with a construction delay of 3 minutes in the centrifuge, representing, in terms of consolidation, approximately 3 weeks at prototype scale.

Tunnel A, being constructed in a Greenfield site, should produce patterns of movement in line with those observed in the single tunnel test. This is shown to be valid by the excellent level of correlation between the LVDT results and the profile generated by a Gaussian curve fitting exercise. Settlements generated by excavation of Tunnel B do not however show this level of agreement due to the presence of the first tunnel. A simple integration of the data shows that the volume loss apparent at the surface is 2.6 % (for 3 % fluid removed from Tunnel A). It can clearly be seen that the maximum settlement generated by the construction of Tunnel B is larger and that the settlements are asymmetric about the tunnel centre-line (60 mm from the box centre-line). The volume loss apparent at the surface due to the construction of Tunnel B is 2.8 % although the volume of fluid extracted from the tunnel cavity remained at 3 %. These observations generally agree with numerical predictions such as those of Hunt (2005) as well as field measurements made at St. James's Park where a larger volume loss was measured upon construction of the second tunnel (Standing *et al.*, 1996).

Conclusions

A series of tests have been performed to examine the surface settlement profile above a single tunnel excavated in clay. The results demonstrate the ability of the apparatus to produce repeatable results whilst allowing close control of the volume loss around the tunnel. There is a remarkable level of correlation between the data obtained and previously published prediction methods.

Having verified the operation of the apparatus a second series of tests investigated the ground behaviour during the construction of a parallel pair of tunnels. Again, a high level of correlation between published data and these experiments was shown upon completion of the first tunnel but settlements generated by construction of the second tunnel are larger and asymmetric about the tunnel centre-line. These dissimilar settlements would suggest that superposition of the settlements caused by Tunnel A would be inadequate to accurately predict the overall movements caused by the system as a whole.

The apparatus design allows for monitoring of surface movements, sub-surface movements and pore pressure changes, although for the purposes of demonstrating the effectiveness only the surface settlements have been discussed here. It is clear that a large amount of data pertaining to both surface and sub-surface effects can potentially be obtained, improving the understanding of a complex soil-structure problem. A reflection of the difficulty in understanding this scenario can be seen by the complexity of the apparatus used.

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Figures and Tables

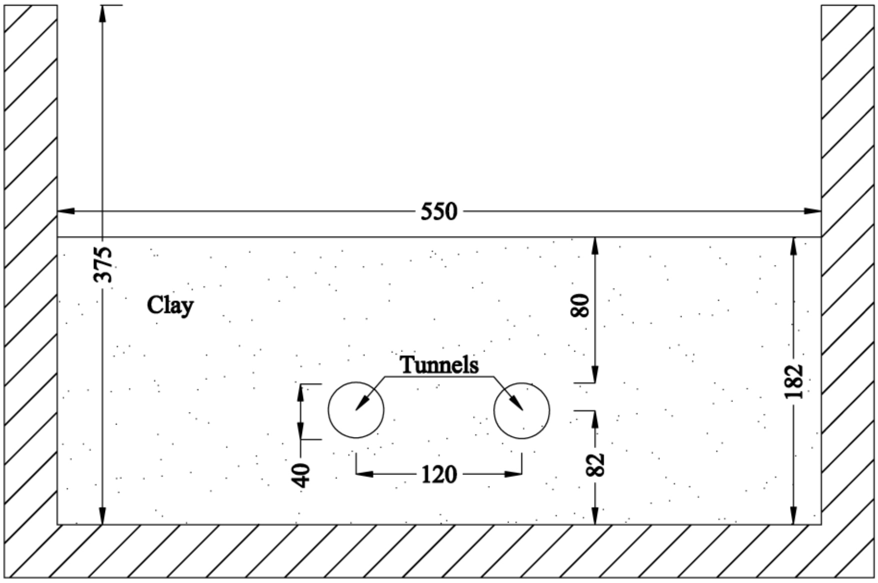

Figure 1: Section through centrifuge model showing a twin-tunnel arrangement (dimensions in mm)

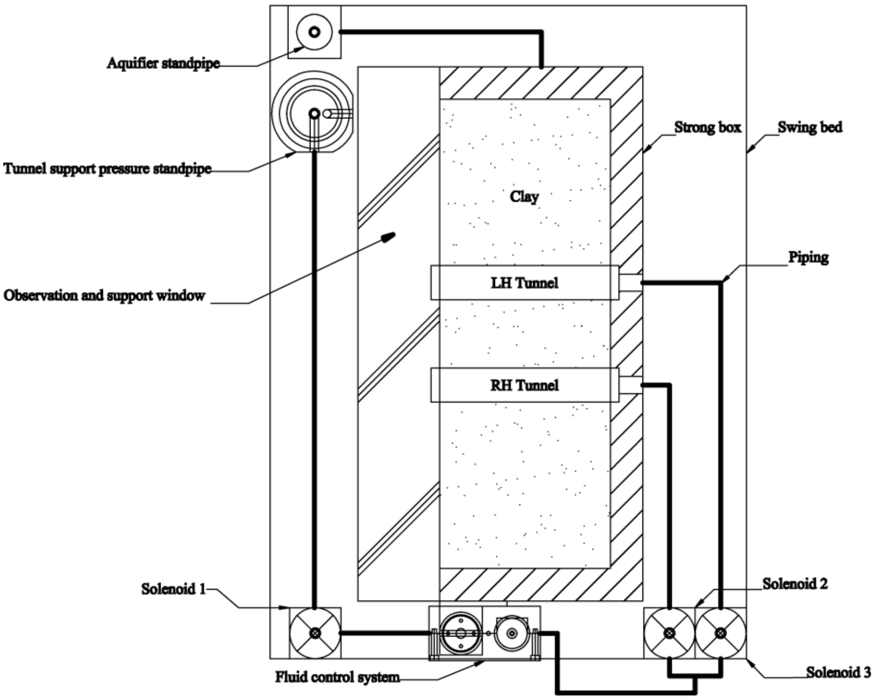

Figure 2: Schematic of fluid flow through Apparatus B

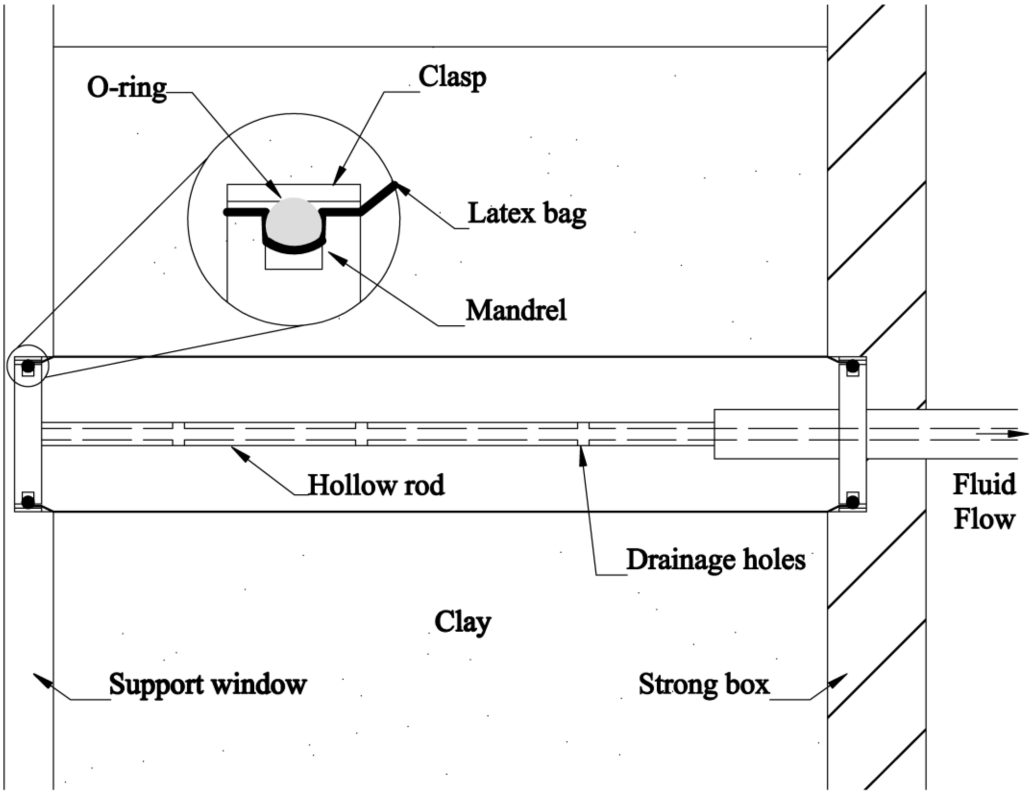

Figure 3: Section through tunnel cavity support apparatus

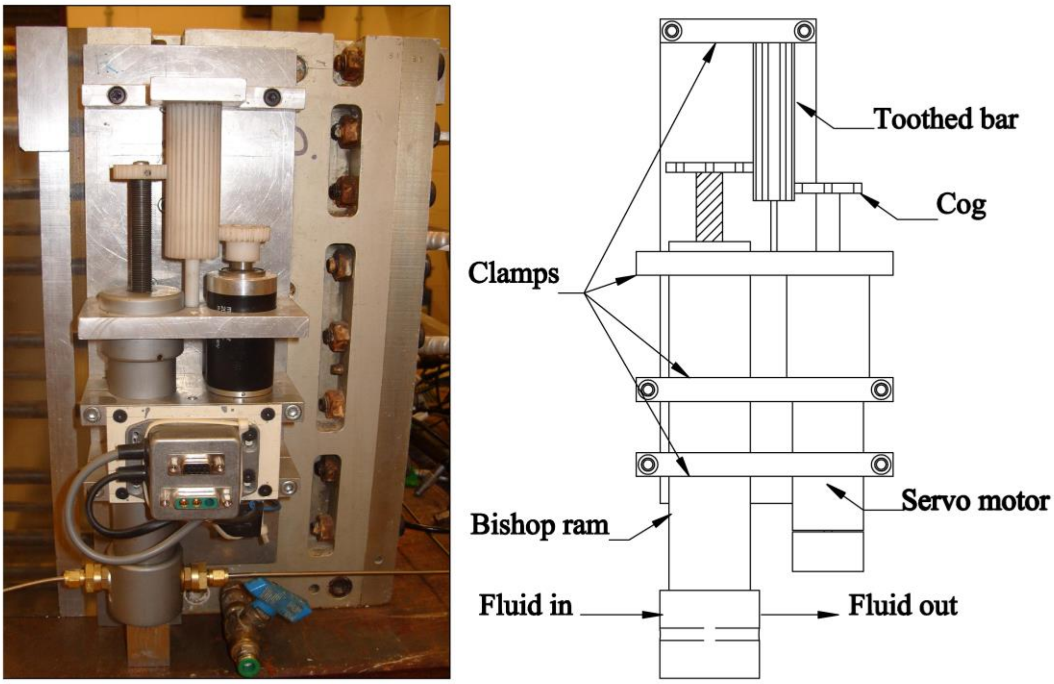

Figure 4: View of the volume loss controlling system

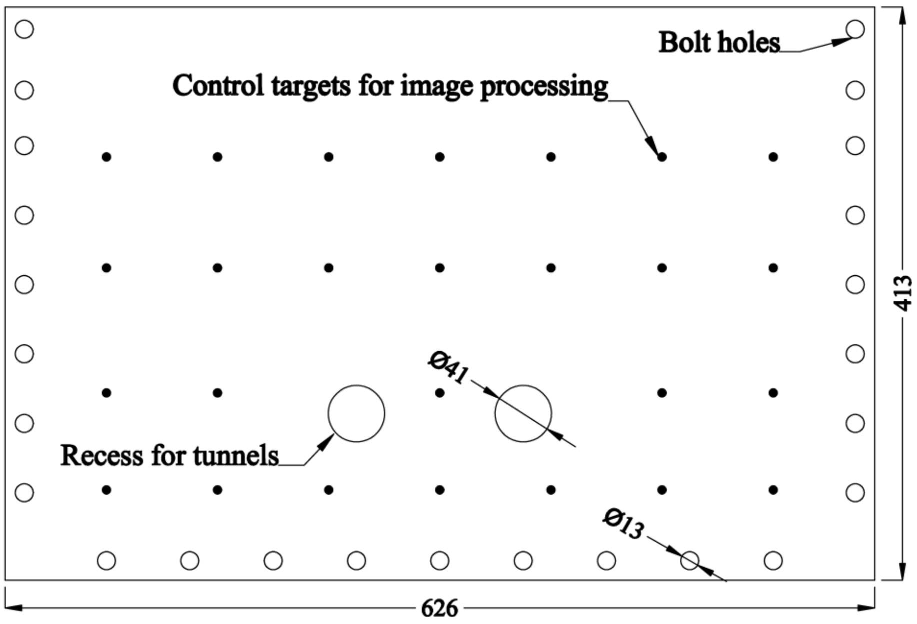

Figure 5: Schematic plan of the Twin-Tunnel Support Window

Figure 6: Adjustable tunnel cutter mounted to strong box and positioned to bore left hand tunnel. Right hand tunnel already bored

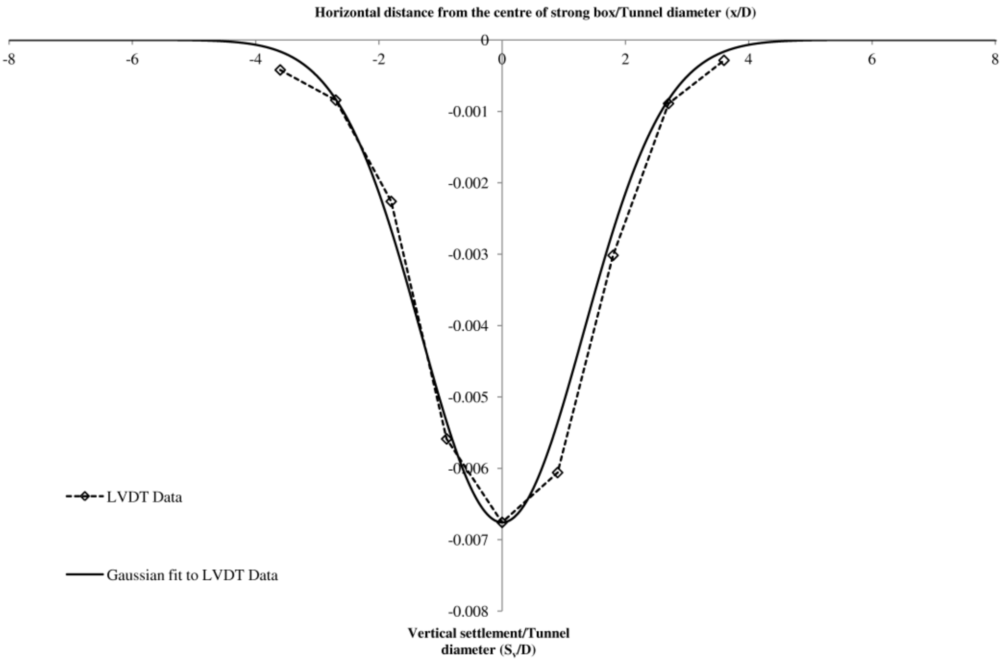

Figure 7: Surface settlement profile following excavation of a single tunnel using Apparatus A

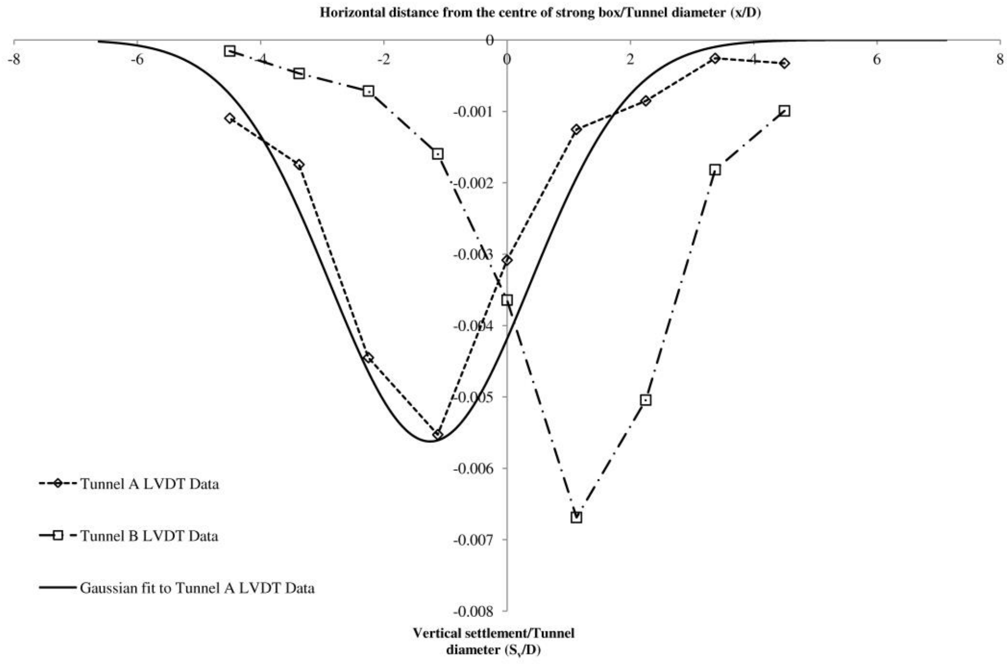

Figure 8: Surface settlements generated by excavation of twin-tunnels using Apparatus B

	S_{max}	i
Experimental data	-337.5 µm	66 mm
Clough & Schmidt (1981)	-451.1 µm	52 mm
Mair *et al.* (1981)	-375.6 µm	63 mm
Verrujit & Booker (1996)	-301.4 µm	78 mm

Table 1: Comparison of experimental data from single tunnel test with published prediction methods